2013

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Jian Liu
Marshall University, jian.liu@marshall.edu

Thurmon E. Lockhart

Recommended Citation

Liu J, Lockhart TE (2013) Aging Effect on Foot Dynamics during Unexpected Slips. Clin Res Foot Ankle 1:107. doi: 10.4172/2329-910X.1000107

Clinical Research on Foot & Ankle

Liu and Lockhart, Clin Res Foot Ankle 2013, 1:2
http://dx.doi.org/10.4172/2329-910X.1000107

Research Article | Open Access

Aging Effect on Foot Dynamics during Unexpected Slips

Jian Liu[1]* and Thurmon E Lockhart[2]

[1]*Division of Applied Science and Technology, Marshall University, Huntington, WV, USA*
[2]*Grado Department of Industrial and Systems Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA*

Abstract

Slip-induced fall accidents have been recognized as a serious threat to the health of the elderly.The objective of the current study was to investigate the aging effect on the biomechanical reactions of both perturbed foot and unperturbed foot to the unexpected slips. Nineteen younger (mean age: 25.0 years old) and twenty-one older (mean age: 71.2 years old) adults were involved in a laboratory study,in which slippery surface was induced during walking without their awareness.The reactive responses of both slipping foot and unperturbed foot were quantified by optical motion capture system and force platforms.The results indicate a characteristic toe-touch strategy by the unperturbed foot after slip starts. Significant aging effects were found in touch down base of support created by the unperturbed foot. It was concluded that the unperturbed foot is important to facilitate successful recovery from unexpected. Specifically, in order to prevent age-related slip-induced falls, it is important for the unperturbed foot to create sufficient base of support in anterior-posterior direction and to control the base of support in media-lateral direction.

Keywords: Slips and falls; Foot kinematics; Fall prevention

Introduction

Slip-induced fall accidents have been recognized as a serious threat to the health of the elderly. Approximately one-third of adults over 70 years of age fall each year [1]. In 2009 alone, 2.2 million older adults visited emergency rooms for fall-related injuries [2]. For any fall prevention approaches to be effective, it is important to understand the age-related slips and fall mechanisms.

The postural responses of the perturbed foot (i.e., slipping foot) have received most of the research attention. Through investigating the reactive ankle joint moments and ankle joint angles of the perturbed foot in the sagittal plane, Cham and Redfern [3] found increased knee flexion and forward rotation of the lower leg in an attempt to bring the perturbed foot closer to the body. Utilizing a 3D inverse dynamics approach, Liu and Lockhart [4] identified the critical role of ankle joint of the perturbed foot in successful recovery from unexpected slips. Further research indicated that the slip distance and peak forward sliding velocity during slip-induced falls were greater than or equal to 10cm and 0.8m/s, respectively [5].

Relative to the literature on perturbed foot responses, little was known about the role of unperturbed foot (i.e., trailing foot) in slips and falls. Earlier study suggested that inter-limb coordination appears to play a role in successful balance recovery after simulated slips on a translating platform [6]. Martigold [7] investigated the whole body coordinative responses to simulated slips, and found that 60% of the subjects (mean age: 21.2 years old) demonstrated a toe-touch reaction. However, there is a gap in knowledge regarding the unperturbed foot dynamics on slippery surface. In addition, previous research has been heavily focused on the younger adults. It is unclear about the role of aging in reactive foot dynamics.

Therefore, the objective of the current study was to investigate the aging effect on the biomechanical reactions of both perturbed foot and unperturbed foot to the unexpected slips. It was hypothesized that there would be significant age-related differences in foot dynamics in both slip-induced falls and successful recoveries.

Materials and Methods

Nineteen younger and twenty-one older adults (Table 1) were involved in a laboratory study. All the subjects were healthy and free from major musculoskeletal injuries as examined by study physician. The study protocol was approved by local Institutional Review Board. Informed consent was obtained prior to data collection.

Details on slip-induced fall protocol can be found in our previous publications [4]. Briefly, subjects were instructed to walk at a normal pace on a linear walkway (1.5 m ×15.5 m) wearing an overhead harness system. Unexpected slips were induced by changing thedry floor surface into slippery surface (covered with 3:1 KY-Jelly and water mixture) without subjects'awareness. The starting point of the walking trial for each subject has been carefully adjusted to ensure that the slip was always initiated at the right heel contact. Two force-plates (Bertec Corporation, OH, USA) and a six-camera ProReflex system (Qualysis, Sweden) were synchronized to collect kinetics and kinematics at a sampling rate of 120Hz. Video recordings and motion capture data were inspected to identify any distinctive motion pattern of unperturbed foot after slips.

The slip trials were categorized into either recovery or fall. Falls were defined as the trials in which the subject has to rely on external assistances (e.g., harness) other than floor support to maintain their balance. Specifically, falls were considered as those trials in which subject's vertical shoulder position (measured by shoulder marker) dropped more than 23 cm from normal shoulder height after slip [4]. All other slip trials were categorized asrecovery.

Foot dynamics of the perturbed foot were quantified by Heel Contact Velocity (HCV), Slip Distance (SD), Peak Sliding Heel Velocity (PSHV), and Required Coefficient Of Friction (RCOF). Computation

***Corresponding author:** Jian liu, Division of Applied Science and Technology, Marshall University, Huntington, WV, USA, Tel: (304)696-3067; E-mail: liuji@marshall.edu

Received January 23, 2013; **Accepted** May 02, 2013; **Published** May 06, 2013

Citation: Liu J, Lockhart TE (2013) Aging Effect on Foot Dynamics during Unexpected Slips. Clin Res Foot Ankle 1: 107. doi:10.4172/2329-910X.1000107

details can be found in our previous publication [8]. Briefly, HCV was defined as the instantaneous horizontal heel velocity at the time of heel contact. SD was defined as the resultant distance travelled by the heel from slip-start to slip-stop. PSHV was defined as the maximum horizontal heel velocity between slip-start and slip-stop. RCOF was defined as the maximum ratio of horizontal and vertical ground reaction force between heel contact and slip-stop.

Foot dynamics of the unperturbed foot were quantified by Touch-Down Time (TDT), Touch-Down Velocity (TDV), Touch-Down Base of Support in Anterior-Posterior direction (TDBoS_AP) and in Medio-Lateral direction (TDBoS_ML).

Touch-down time (TDT)

TDT was defined as the time interval between slip start and unperturbed foot touch down. Slip start was defined as the point where forward heel acceleration of the perturb foot after heel contact occurred [8]. Unperturbed foot touchdown was defined as the point where the unperturbed foot contacts the ground after the proceeding toe-off, from kinematic trajectory of toe marker using a similar algorithm by Ghoussayni et al. [9]. As a timing variable, TDT was meant to measure how quick the unperturbed foot reacted to the unexpected slips.

Touch-down velocity (TDV)

TDV was defined as the anterior-posterior velocity of the unperturbed foot Center-Of-Mass (COM) at the time of unperturbed foot touch down. As a kinematic variable, TDV was meant to provide velocity information of the unperturbed foot in response to the unexpected slips.

Touch-down base of support (TDBoS)

TDBoS was defined as the area between toe position of the unperturbed foot and heel position of the perturbed foot at the time of unperturbed foot touch down. TDBoS was quantified in both anterio-posterior (AP) andmedio-lateral (ML) directions.

A one-way between-subject MANOVA was performed with age group (young and old) as the independent variable and slip outcome (recovery and fall) as the blocking variable. The dependent variables include HCV, SD, PSHV, RCOF, TDT, TDV, TDBoS AP, and TDBoS_ML. A significant level of $p \leq 0.05$ was adopted for hypothesis testing. All statistical analyses were performed in JMP 10 (SAS Institute Inc., USA).

Results

Summary of the slip trials is presented in Table 2. More than half of the older subjects fell on the slippery surface, while less than one third of the younger subjects fell. Inspection of motion capture data together with video recordings indicated that the unperturbed foot adopted a characteristic reactive strategy. The unperturbed foot would typically complete the toe-off phase that usually occurred before slip start. Shortly after the perturbed foot started slipping (at the time of heel contact), the unperturbed foot stopped its swing phase and toe-touched the ground to create a base of support.Seven subjects did not complete the toe-off phase after slip initiation, and thus did not utilize the toe-touch strategy. During recovery, the time from slip start to unperturbed foot touch down was, in average, 284.6ms and 255.0ms for the younger subjects and older subjects, respectively (Table 3). The typical TDV during recovery was found to be 308.8cm/s and 288.1 cm/s for the younger subjects and older subjects, respectively (Table 3).

	Young (18-30 yrs)	Old (65-85 yrs)
Age(year)	25.0 (3.0)*	71.2 (5.5)
Weight(kg)	66.9 (14.9)	71.8 (14.1)
Height(cm)	170.9 (10.1)	161.8 (7.3)

*mean (standard deviation)

Table 1: Summary of Anthropometric Information

Group	Recovery	Fall
Old	10	11
Young	13	6

Table 2: Slip outcome summary.

Significant aging effect was found in TDBoS in both AP and ML directions (Table 3). Specifically, during recovery, the younger subjects (mean =49.4) were found to generate a significantly higher TDBoS_AP (p =0.0072) than the older subjects (mean =26.6 cm). During falls, the older subjects (mean =20.2) created a significantly higher TDBoS_ML (p =0.0036) than the younger subjects (mean =7.2 cm). No significant aging effect was found in either TDT or TDV.

For the perturbed foot, significant aging effects were found in both RCOF and HCV (Table 4). In both fall (p =0.0047) and recovery (0.0001) trials, the RCOF was found to be significantly higher in younger subjects (mean in fall=0.21, mean in recovery=0.20) than in older subjects (mean in fall=0.17, mean in recovery=0.17). In other words, the younger adults typically require higher friction from the floor surface during walking than the older adults. During recovery, the HCV was also found to be significantly faster (p =0.0065) in younger subjects (mean =116.0 cm/s) than older subjects (mean=90.9 cm/s). No significant aging effect was evident in either SD or PSHV.

Discussion

The objective of the current study was to investigatethe aging effect on the biomechanical reactions of both perturbed foot and unperturbed foot to the unexpected slips. As hypothesized, significant age-related differences were evident in the biomechanical parameters of both perturbed foot and unperturbed.

For the unperturbed foot, a characteristic toe-touch strategy was found to be employed by most subjects in the current study. Such strategy was characterized by completed toe-off of the unperturbed foot followed by a rapid touch down on the floor surface. Similar toe-touch strategy has been observed in a previous study [7], in which the subjects rapidly lowered their unperturbed limb and demonstrated a toe-touch response. In another study [10], however, the typical reactive response of the unperturbed foot was heel-contact, instead of toe-touch.Such difference in reaction strategy could be due to the fact that the metronome was used to regular the gait in the latter study.

The role of unperturbed foot in preventing age-related falls could be explained from the perspective of base-of-support. In the current study, no aging effect was evident in either TDT or TDV. In other words, how quick the instantaneous base of support can be created after slipping may be less important in preventing falls. Nevertheless, the significant higher base of support in AP direction by the younger subjects may help explain why the younger adults experience fewer falls after slipping. It should be noted larger base of support may not necessarily offer benefits to recovery, considering the fact that BoA_ML was significantly higher in older subjects during falls. Together, it can be postulated that in order to prevent age-related falls, it may be beneficial to generate higher BoS in AP direction and well-controlled BoS in ML direction.

Parameters	Slip Outcome	Old	Young	p-value
TDV* (cm/s)	Fall	293.4 (57.4)	234.6 (165.1)**	0.3937
	Recovery	288.1 (71.9)	308.8 (62.1)	0.4939
TDT (ms)	Fall	415.4 (354.7)	248.3 (46.2)	0.2753
	Recovery	255.0 (22.2)	284.6 (48.6)	0.0892
TDBoS_AP (cm)	Fall	51.7 (23.0)	65.1 (22.1)	0.26
	Recovery	26.6 (18.7)	49.4 (17.8)	0.0072***
TDBoS_ML (cm)	Fall	20.2 (7.4)	7.2 (7.5)	0.0036***
	Recovery	20.0 (4.6)	17.1 (6.6)	0.2482

*TDV: Touch Down Velocity; TDT: Touch Down Time; TDBoS_AP: Touch Down Base of Support in Anterio-Posterior direction; TDBoS_ML: Touch Down Base of Support in Medio-Lateral direction

**mean (standard deviation)

***indicates significant aging effect

Table 3: Biomechanics of unperturbed foot

Parameters	Slip Outcome	Old	Young	p-value
SD* (cm)	Fall	35.7 (13.7)**	42.4 (27.5)	0.5060
	Recovery	14.8 (5.2)	21.2 (11.8)	0.1252
PSHV (cm/s)	Fall	247.1 (28.8)	277.5 (66.4)	0.2026
	Recovery	173.4 (54.0)	188.4 (64.4)	0.5589
HCV (cm/s)	Fall	85.8 (18.5)	74.6 (17.2)	0.3108
	Recovery	90.9 (9.8)	116.0 (23.3)	0.0065***
RCOF	Fall	0.17 (0.02)	0.21 (0.03)	0.0047***
	Recovery	0.15 (0.02)	0.20 (0.03)	0.0001***

*SD: Slip Distance; PSHV: Peak Sliding Heel Velocity; HCV: Heel Contact Velocity; RCOF: Required Coefficient of Friction

**mean (standard deviation)

***indicates significant aging effect

Table 4: Biomechanics of perturbed foot

The role of unperturbed foot in preventing slip-induced falls can be further highlighted by the slip outcomes without utilizing the toe-touch strategy. As indicated in the results, seven subjects did not complete the toe-off phase, and they all fell in the study. Similar findings were also reported in literature [10].

For the perturbed foot, the younger adults were found to generate faster heel contact velocity and require higher coefficient of friction than their older counterparts. Both HCV and RCOF were found to positively correlate with the risk of falling [8]. Nevertheless, the younger subjects still fell less than the older subjects in the current study. Therefore, this seemingly contradicting result may further support the role of unperturbed foot in preventing falls.

Admittedly, the current study had several limitations that should be addressed in future studies. Due to limited sample size, the slip outcome was considered a blocking factor, instead of an independent variable. Future studies comparing foot dynamics between recoveries and falls are warranted. In addition, it will also expand our knowledge to investigate the upper limb contributions to successful recovery and the possible interaction effect between upper limb reactions and foot dynamics during unexpected slips.

In conclusion, a characteristic toe-touch strategy adopted by the unperturbed was evident during unexpected slips. In order to prevent age-related slip-induced falls, it is important for the unperturbed foot to create sufficient base of support in AP direction and to control the base of support in ML direction.

Acknowledgement

This research was supported by the National Institute of Occupational Safety and HealthGrant CDC/NIOSH R01-OH009222. The paper's contents are solely the responsibility of the authors and do not necessarily represent the official views of the NIOSH.

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